

AD-A159 129

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REPORT DOCUMENTATION PAGE

1. SECURITY CLASSIFICATION Unclassified			1b. RESTRICTIVE MARKINGS			
2a. SECURITY CLASSIFICATION AUTHORITY			3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; Distribution unlimited			
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE						
4. PERFORMING ORGANIZATION REPORT NUMBER(S)			5. MONITORING ORGANIZATION REPORT NUMBER(S) AFOSR-TR- 85-0717 N/A			
6a. NAME OF PERFORMING ORGANIZATION NORSAR		6b. OFFICE SYMBOL (If applicable)		7a. NAME OF MONITORING ORGANIZATION AFOSR/NP		
6c. ADDRESS (City, State and ZIP Code) NTNF/NORSAR P.O. Box 51 N-2007 Kjeller			7b. ADDRESS (City, State and ZIP Code) Building 410 Bolling AFB, DC 20332-6448			
8a. NAME OF FUNDING/SPONSORING ORGANIZATION AFOSR		8b. OFFICE SYMBOL (If applicable) NP		9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER F49620-85-C-0016		
8c. ADDRESS (City, State and ZIP Code) Building 410 Bolling AFB DC 20332-6448			10. SOURCE OF FUNDING NOS.			
			PROGRAM ELEMENT NO. 61102F	PROJECT NO. 2309	TASK NO. A1	WORK UNIT NO. N/A
11. TITLE (Include Security Classification) DEVELOPMENT AND EVALUATION OF A REGIONAL SEISMIC ARRAY IN NORWAY						
12. PERSONAL AUTHOR(S)						
13a. TYPE OF REPORT Quarterly Technical		13b. TIME COVERED FROM 1-1-85 TO 31-3-85		14. DATE OF REPORT (Yr., Mo., Day) 30 APR 85		
15. PAGE COUNT 36						
16. SUPPLEMENTARY NOTATION						
17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)			
FIELD	GROUP	SUB. GR.				
19. ABSTRACT (Continue on reverse if necessary and identify by block number) Field installations have been operating Very reliably during the reporting period. Sources of rather minor errors in the data were traced in close cooperation with Sandia, and appropriate actions were taken to midify the field system to eliminate these errors. Computer equipment for acquision and processing of the NORESS data has been purchased and installed. All data recieved at Kjeller are now subjected to online processing for detection and location of seismic events. The RONAP program package, developed at NORSAR during the last couple of years, has been adapted for use on the new data. An advanced status monitoring system has been developed. This system generates statistics on all essential aspects of operations of the new array, and suitable units for display of essential parameters have been aquired and installed.						
20. DISTRIBUTION/AVAILABILITY OF ABSTRACT UNCLASSIFIED/UNLIMITED <input checked="" type="checkbox"/> SAME AS RPT. <input checked="" type="checkbox"/> DTIC USERS <input type="checkbox"/>			21. ABSTRACT SECURITY CLASSIFICATION Unclassified			
22a. NAME OF RESPONSIBLE INDIVIDUAL Ralph E Kelley			22b. TELEPHONE NUMBER (Include Area Code) 202-767-4908		22c. OFFICE SYMBOL NP	

ADA159129

QUARTERLY TECHNICAL REPORT

01 January 1985 - 31 March 1985

for project

SEISMIC
DEVELOPMENT AND EVALUATION OF A REGIONAL ~~SEISMIC~~ ARRAY IN NORWAY



Edited
by

Svein Mykkeltveit

Kjeller, 30 April 1985

Accession For	
NTIS GRA&I	<input checked="" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By _____	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A-1	

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Advanced Research Projects Agency (DOD)
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MATTHEW J. KERPEN
Chief, Technical Information Division

1. SUMMARY

This report gives an account of the work conducted by NORSAR in conjunction with development and evaluation of a new regional array in Norway during the period January-March 1985 under Contract F49620-85-C-0016.

The purpose of the development of an experimental regional array in Norway is to take advantage of the extremely good propagation of high-frequency energy for regional seismic phases in Eurasia. Since Norway is located within the same geologic plate boundary as the Soviet Union, the deployment of such an array in Norway provides important new insight with respect to the projected performance of possible future in-country stations in the U.S.S.R.

The field installations have been operating very reliable during the reporting period. Sources of rather minor errors in the data were traced in close cooperation with Sandia, and appropriate actions were taken to modify the field system to eliminate these errors.

The performance of the NORESS Earth Station for transmission of seismic data to the U.S. has also been good during the period January-March. Some problems regarding the stability of the transmission frequency were solved in March through installation by COMSAT General of a new oscillator. The Norwegian Telecommunications Administration (NTA) is now in control of the NORESS Earth Station from NTA's earth station at Eik, Rogaland, Norway.

The 64 kbits/s land line for transmission of data from NORESS to Kjeller became operational on January 2, 1985. During January-March the uptime for the line was 93%. Except for two long outage periods during weekends, the uptime was 98%.

During the reporting period, computer equipment for acquisition and processing of the NORESS data has been purchased and installed. All data received at Kjeller are now subjected to online processing for detection and location of seismic events. The RONAP program package, developed at NORSAR during the last couple of years, has been adapted for use on the new data.

An advanced status monitoring system has been developed. This system generates statistics on all essential aspects of operations of the new array, and suitable units for display of essential parameters have been acquired and installed. An alarm system has been developed for outside-office-hours routing of alarms (via the public telephone network) to the person assigned to on-call duty.

This report also contains two contributions on event detection and location capabilities of the NORESS array. Although some of the work in these contributions is performed as part of our research program covered by another contract with DARPA, these contributions are included here for the sake of completeness. These preliminary evaluations have shown that the new array has an excellent teleseismic detection for most of Eurasia, with many small detections that have been missed by the NORSAR detector. The performance for local and regional phases is also very good, whereas some problems have been encountered in the automatic detection of L_g phases.

Our investigations indicate that beamforming gains exceeding \sqrt{N} can be obtained for P phases. For secondary phases like S_n and L_g , there is also some gain from beamforming, although not of the order of \sqrt{N} . The location capability of NORESS has been evaluated from bearing estimates derived from FK-analysis of regional phases, and our results indicate that, when due care is taken in selecting the analysis frequency, these estimates are within 5° of the true values.

II. GENERAL BACKGROUND

The purpose of the development of the regional NORESS array in Norway has been to take advantage of the extremely good propagation of high-frequency energy for regional seismic phases in Eurasia. Since Norway is located within the same geologic plate boundary as the Soviet Union, the deployment of such an array in Norway provides important new insight with respect to the projected performance of possible future in-country station in the U.S.S.R.

The array was constructed in Norway as a joint enterprise between Sandia National Laboratories, Albuquerque, U.S., and NORSAR, and initial data from the array were available from September 1984. Seismic data are being transmitted via satellite to several recipients in the U.S., and from January 1985 via a 64 kbits/s digital land line to the NORSAR Data Processing Center at Kjeller.

Over the past five years, NORSAR has conducted extensive field experiments to assess the potential of regional arrays in detection and location of regional seismic events. Results obtained from this work have been directly utilized in the planning and design work for the new array. The current and previous NORSAR research contracts with DARPA have contained several tasks that relate directly to the processing of data from regional arrays like the new NORESS array now implemented. In particular, a processing package (RONAPP) for on-line detection and location of regional seismic events has been developed and tested. The data from the new NORESS array are now being subjected to real-time processing using the RONAPP algorithm.

Under an FY84 contract, DARPA provided funds for the initial deployment of the new NORESS array. This involved funds for site preparation work and also initial purchases for the data processing center at Kjeller. Additional items for the data processing center have been acquired under the current contract which also provides funds for further developments and evaluations of the new NORESS array.

S. Mykkeltveit

III. FIELD INSTALLATIONS

III.1. Modifications and changes

During the reporting period, a sequence of testing and trouble-shooting on field hardware was carried out in close cooperations with Sandia, in order to locate sources of errors in the data from the array. The modifications amounted to adding filters to the data channels at the point where the data enter the hub station via the fiber optic cables. These modifications were implemented sequentially, so as to allow for evaluation of the performance after each step. In addition, the origin of some errors were traced back to bad connections at the point where the fibre optic cables enter the junction boxes in the hub station. Better support of the cables proved to give better contact and reduced error rates. After these changes which were completed in March, the error rate has been very low. The independent transmission of the data both to Sandia, Albuquerque via the satellite link, and to NORSAR, Kjeller via the land line, made it possible to isolate the origin of errors in the recorded data. Thus, an extensive exchange (via telex) of error statistics generated at Kjeller and in Albuquerque has been essential in locating the error sources. Apart from these minor problems with the hardware, the overall status of the field installations has been excellent.

III.2 Maintenance and repair

The array site was visited almost daily by our field technicians in this initial phase of operation of the NORESS array. A couple of cards for transmission of data via the fiber optic cables were replaced, due to malfunction.

No problem occurred during the reporting period, that could be associated with the site construction work of the last summer. Specifically, there have been no water leakages in vaults or boreholes and no broken trenched cables.

S. Mykkeltveit

IV DATA TRANSMISSION

The block diagram of Fig. IV.1.1 shows the NORESS data flow. From the hub station, data are transmitted via a land line to the NORESS central computer located at the NORSAR Data Processing Center at Kjeller. Simultaneously, there is communication via satellite to receiving stations at cooperating institutions in the U.S. The Norwegian Telecommunication Administration (NTA) is responsible towards Intelsat for operation of the satellite earth station located at the NORESS hub station. A telephone link to an NTA control center provides NTA with necessary information on the performance of the earth station.

IV.1 Satellite transmission of data to the U.S.

The performance of the NORESS Earth Station for transmission of seismic data to the U.S has been good during the reporting period. Problems regarding the stability of the transmission frequency were solved in March through installation by COMSAT General of a new oscillator. NTA is now in control of the NORESS Earth Station from its earth station at Eik, Rogaland, Norway. This arrangement, required by INTELSAT, was implemented in March and replaced the temporary arrangement that allowed NTA to control the NORESS Earth Station from Tryvann, Oslo. As indicated in Fig IV.1.1 there is a dual connection between the NTA control point and NORESS. This provides for a backup in case of failure of one of the lines. NTA has required that the satellite transmission to the U.S must halt when both control lines fail, since in these circumstances NTA would be out of control of the Earth Station. Thus, the arrangement with backup line serves to improve the reliability of the system. Outages for the satellite transmission during the reporting period were as follows, with reason for outage indicated:

Jan. 10, 1305-1321gmt, due to frequency adjustment
Jan. 15, 1400-1410gmt, due to frequency adjustment
Jan. 23, 1330-1335gmt, due to frequency adjustment
Jan. 28, 1714-1716gmt, due to frequency adjustment

Feb. 05, 1504-1506gmt, due to frequency adjustment
Feb. 08, 1915-1947gmt, due to frequency adjustment
Feb. 18, 1436-1439gmt, due to frequency adjustment
Feb. 26, 1016-1018gmt, due to frequency adjustment

In addition, there was an outage in the period Feb. 25, 1500gmt - Feb. 26, 1000gmt due to failure of the telex line for remote control of the NORESS earth station from the NTA control point in Oslo.

Mar. 11, 1039-1042gmt, due to frequency adjustment
Mar. 14, 0730-0859gmt, due to installation of new control line
Mar. 14, 1038-1117gmt, due to installation of new control line
Mar. 15, short outage at 0752gmt, due to installation of new control line
Mar. 18, many short outages during 0900-1330, due to installation of new control line.

IV.2 Land line to Kjeller

The new 64 kbits/s digital land line for transmission of data from the array to NORSAR's data processing center at Kjeller became operational on January 2, 1985. During the period January 2 - March 31 the uptime for the line has been 93%. Excluding two extended outage periods (one each in February and March) the uptime is 98%. The long outage periods occur during weekends. We are currently discussing with NTA the possibility of repair services during weekends, which they do not offer at present. Fig. IV.2.1 shows the uptime for each day in the three months period January - March 1985 for the entire NORESS system with field installation, transmission lines and data acquisition at Kjeller. Since nearly all failures to record data at Kjeller are due to problems with the land line, the uptime statistics in Fig. IV.2.1 reflect the uptime for the 64 kbits/s land line.

S. Mykkeltveit

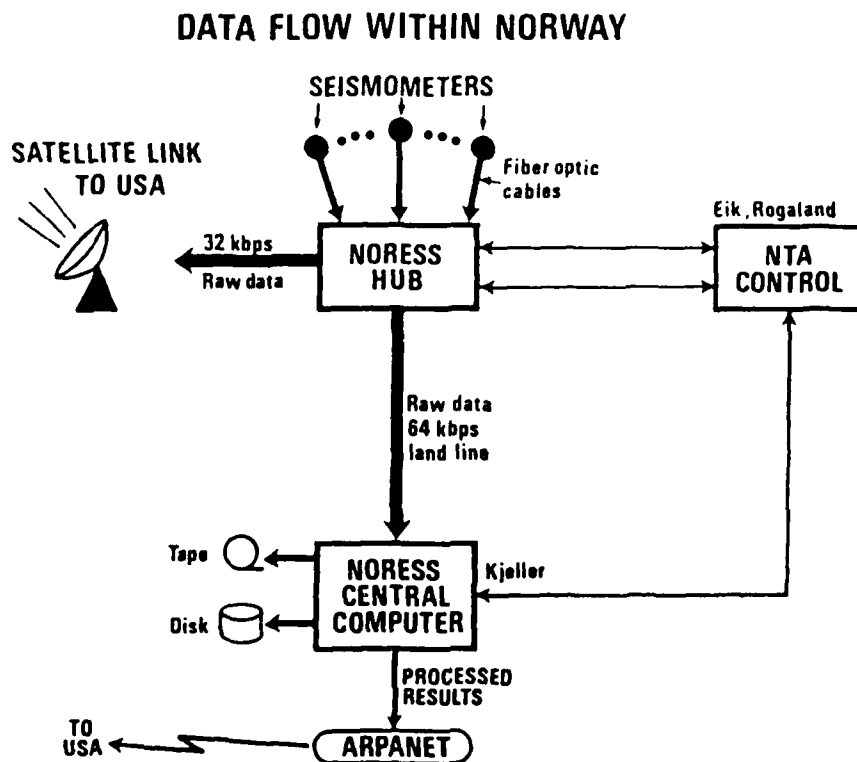


Fig. IV.1.1 The figure shows schematically the NORESS data flow with local transmission in the field, transmission by leased telephone lines from the central field site to the Kjeller Data Center, and external exchange of data and processing results. Via satellite the seismic data are transmitted to three institutions in the US: Sandia National Laboratory in Albuquerque, Lawrence Livermore National Laboratory, Livermore and the center for Seismic Studies in Rosslyn, Virginia

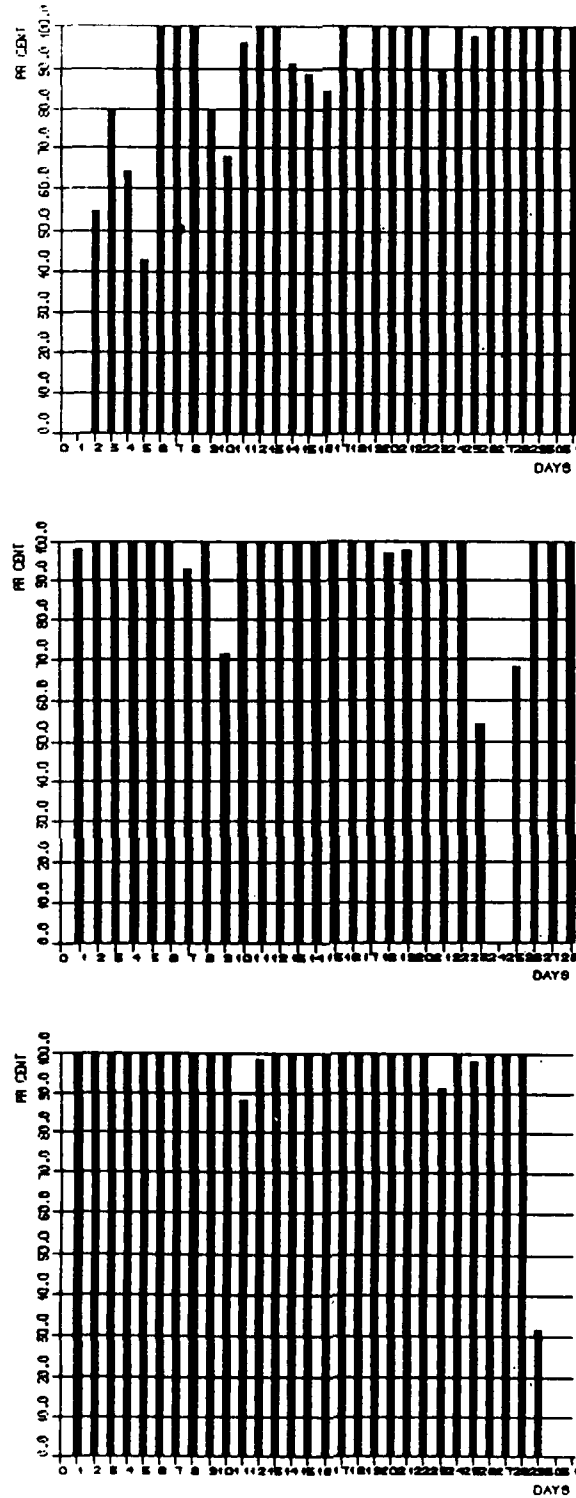


Fig. IV.2.1 NORESS system uptime for January (top), February (middle) and March 1985 (bottom)

V. DATA CENTER OPERATIONS

V.1 Equipment implementations

During the reporting period, data processing equipment specified under the next section of this report was installed. This equipment is used for acquisition and analysis of data at the Kjeller data center. The data processing equipment comprises items for both on-line and off-line data analysis. All items were implemented during the reporting period and are operating technically satisfactorily. A detailed description of the entire acquisition and data processing system at Kjeller will be given in the next quarterly technical report due July 30, 1985.

For technically complex systems such as the NORESS array, it is of utmost importance to develop advanced capabilities of monitoring and control of all operational aspects. This is achieved by including a number of state-of-health parameters in the data stream itself and subject these parameters to close surveillance at the data center. About 20% of the data received from NORESS concern the system's state-of-health, and include environmental parameters like humidity and temperature in all vaults and wind speed and directions at the central hub station. More important, the data carry extensive information on how well the array functions from a technical point of view, and this information enables us to critically survey performance of the field installation, status of transmission lines and recording of data at the data center, all in a fully automated mode. In fact, failure to record data at any time triggers an alarm that reaches the operator on duty. The block diagrams of Fig. V.1.1 give details on system components subject to regular and emergency-type monitoring and actions taken in case of failure of vital array functions.

V.2 Real time data processing

The flow chart of Fig. V.2.1 illustrates the real time detection processing of data from NORESS. The detection processor for NORESS can be briefly described as follows: Beams (both conventional and incoherent) are formed to enhance weak signals, the beams are filtered to further suppress the background noise and the STA/LTA (STA = short-term "power" average, LTA = long-term average) ratio calculated for each beam at a certain rate, for detection of seismic signals above a specified threshold.

Once a signal has been detected, it is subject to frequency-wavenumber analysis for direct estimation of direction of arrival and wave speed (phase velocity) across the array. This technique amounts to computing a very high number (typically of the order of several thousand) of beams and comparing them to find the one that best enhances the signal.

The actual declaration and location of a regional seismic event rely on a successful association of a P- and S-wave arrival from that event. The wave type (P or S) is determined by the estimated phase velocity (P-velocity typically of the order of 8 km/s and S-velocity approximately 4 km/s), whereas a common direction of arrival between the P- and S-phases indicates that the observed signals originate from the same event. The difference in arrival time between the two phases converts directly into an epicentral distance, which together with the estimated direction of arrival determine the event location.

A preliminary seismological evaluation of the performance of the real time event detection using the RONAPP processing package is given in the next section, where also examples of the automatic processor output are shown.

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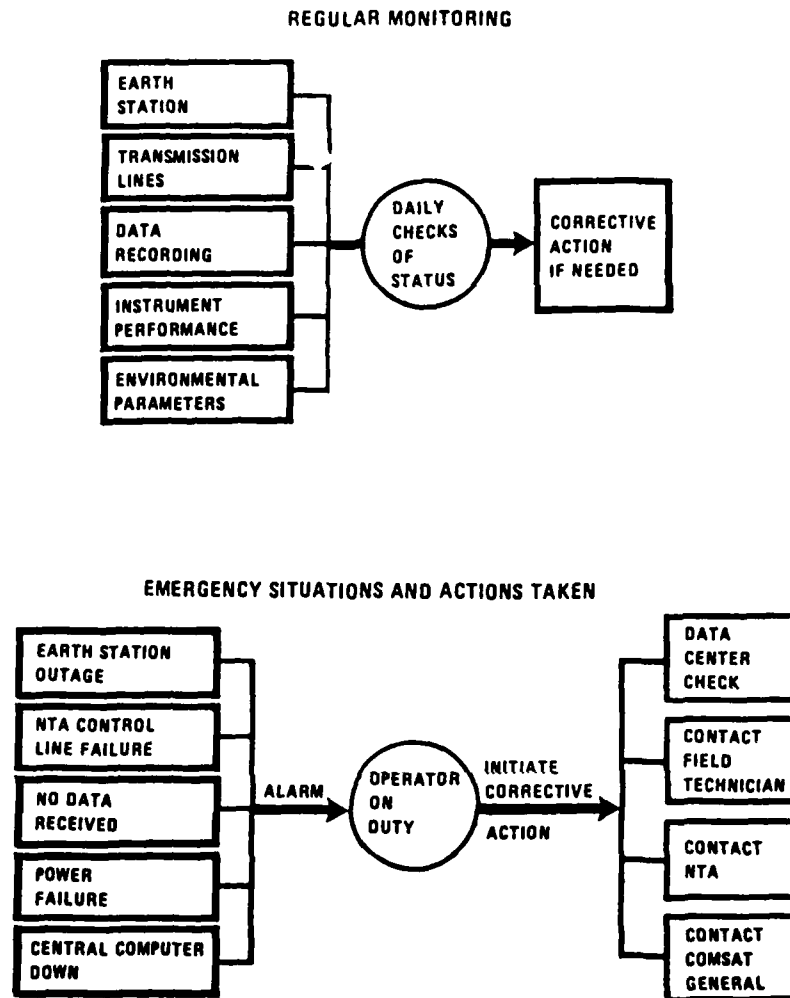


Fig. V.1.1. The block diagrams illustrates how NORESS is subject to regular and emergency-type monitoring. Failure to record data at any time triggers an alarm that reaches the operator on duty.

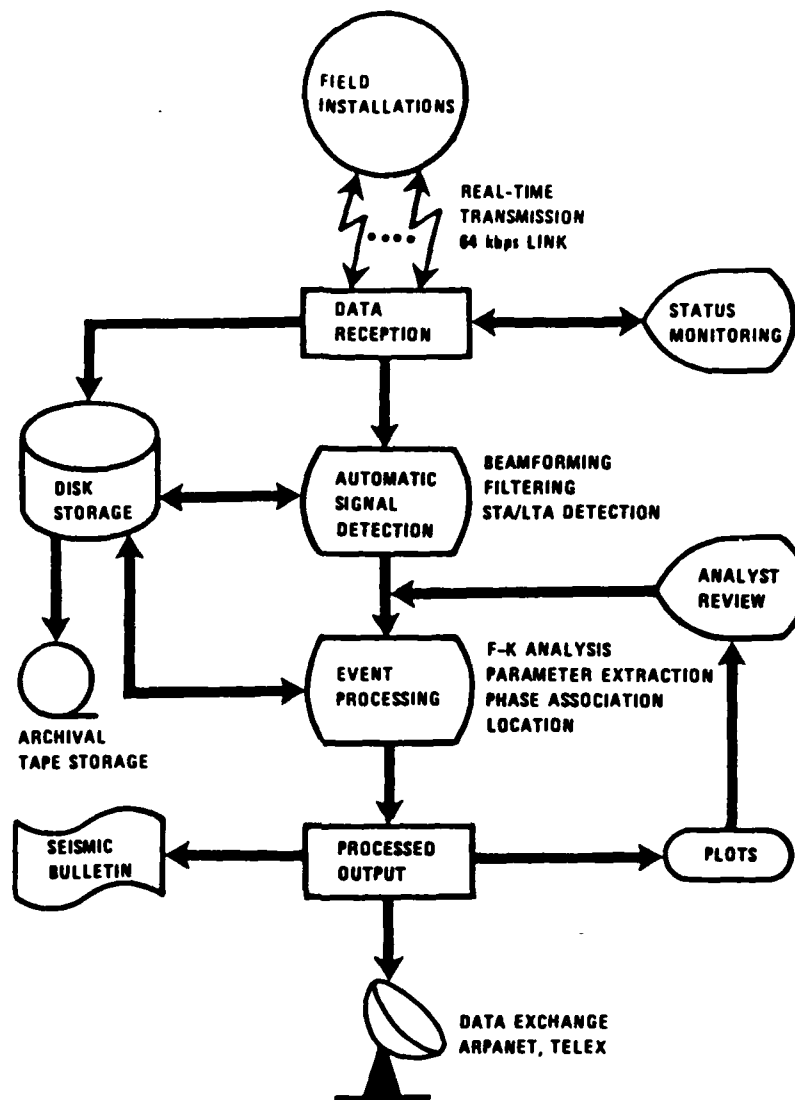


Fig. V.2.1

Flow chart to illustrate the real time detection processing of data from NORESS.

VI. EQUIPMENT PURCHASED

The following equipment, for use in the maintenance of the field installation has been purchased during the reporting period:

Spectrum analyzer
Miniscope, battery
Logic analyzer
Protocol analyzer
Oscilloscope
Paper recorder
Frequency counter
Digital voltmeter
Radio telephones, 2

The following equipment for the data acquisition and processing center at Kjeller has been purchased and installed during the reporting period:

Disk, 4*590 Mbytes, 4
Storage Controller
Computer upgrade
Tape drives, 2
Graphic color terminals, 4
High resolution color graphics
work Station
Upgrade of 3274 controller
Vector to raster converter
22" raster plotter
IBM XT/370
Printer
Alarm unit
Video screens, 3
Control panel, etc.
Terminal for line testing
Tape unit for line testing
IBM/XT

S. Mykkeltveit

VII. PRELIMINARY EVALUATION OF NORESS ARRAY CAPABILITIES

VII.1 Real time event detection using RONAPP

Since January 1985 data from NORESS have been processed in real time at the NORSAR data center at Kjeller. The data used in the detection processing comprise the 25 SPZ channels. The RONAPP detection algorithm has been described by Mykkeltveit and Bungum (1984), and briefly consists of

- Digital narrow-band filtering (six filters)
- Beamforming (conventional and incoherent)
- STA/LTA detector applied to each beam
- Frequency-wavenumber analysis of detected signals
- Association of regional phases to aid in locating events.

In the following, initial results from this processing are described, together with recommendation for future research.

Teleseismic events

The P-wave signal-to-noise ratio at NORESS typically peaks in the 2-4 Hz band for teleseismic events in Eurasia, whereas lower dominant frequency is often observed for signals from the western hemisphere and for epicentral distances exceeding 70 degrees. Signal coherency is naturally very good for teleseismic P across NORESS, even at very high frequencies. Depending on signal frequency, the best beam SNR is obtained using various subsets of the array; e.g., at 2 Hz the best subset consists of the center instrument A0 together with the C and D rings (see Fig. VII.1.1). Using this subset, the beamforming gain meets or exceeds \sqrt{N} , due to the noise suppression characteristics described in the next paragraph.

An example of teleseismic processing results from NORESS is given in Fig. VII.1.2. The improvement in SNR on the beam relative to the single sensors is quite remarkable.

The on-line procedure uses steered teleseismic beams rather than a single infinite-velocity beam for each filter. The resulting SNR gain is, as an example, 4-5 dB for an apparent velocity of 16 km/s, at 3 Hz frequency. For lower frequencies or higher velocities, the gain is less. Thus, applying only infinite-velocity beamforming for teleseismic detection is a viable alternative, in view of the possibility of operating at a lower detection threshold with the same false alarm rate.

The NORESS array detects many teleseismic signals not observed at the large aperture NORSAR array, which, like NORESS, is located in southeastern Norway; especially from selected regions in Eurasia. On the other hand, the signal focusing effects underneath NORSAR cause some instruments to have up to an order of magnitude stronger signals than NORESS sensors, for regions such as Hindu Kush and the Kuriles. For these regions, NORESS does not match the NORSAR detection capability.

Because of the small aperture of NORESS, only a very coarse automatic estimate of the location of teleseismic events is currently being made. Azimuth errors depend on phase velocity and frequency, and are often around 5-10 degrees for small events. Slowness estimates from the automatic process are typically about 1 sec/deg different from those of NORSAR. Nevertheless, it is clear that location estimates from a small array like NORESS will be very valuable to provide a starting point for association procedures using a seismic network. Regional corrections and more detailed off-line analysis are required to assess the eventual capabilities of the array in this regard.

Local and regional events

At local and regional distances, the best SNR for the P wave varies from 3-5 Hz (at around 1000 km) to more than 8 Hz (local distances). Consequently, either steered beams or incoherent beamforming is necessary to exploit the array capability. P-signal coherency at NORESS is usually good enough to utilize the full array for F-K processing of local and regional P-phases, at least up to about 6-8 Hz.

The Lg phase is usually of slightly lower frequency than P. Conventional beamforming is not very efficient for Lg, since the preceding coda (from Sn) comes in with about the same phase velocity and azimuth. Consequently, little "noise" suppression takes place. A promising approach is that of performing narrow-band filtering at several frequencies for the purpose of Lg detection. It turns out that the SNR is greatly improved in those frequency bands where P and Sn coda energy are low relative to the Lg energy. Combining narrow-band filtering with incoherent beamforming has been found particularly effective.

An example of a complete record from a regional event processed at NORESS is given in Fig. VII.1.3. The detection times for P and Lg are marked on the panel of Fig. VII.1.3a, whereas Fig. VII.1.3b shows F-K solutions for P and Lg together with short plots of each phase in an expanded time scale. The estimated azimuths for P and Lg differ by 2 degrees in this case; and a deviation of 0-5 degrees is common. However, a difference of 10 degrees and more is also fairly often observed in the automatic solution.

The location accuracy of NORESS for regional events is currently being studied. No statistically reliable results are available so far due to the limited data base of known locations. The procedure of locating events by associating P and Lg is applicable only up to about 1200 km distance. At greater distances, the Lg usually is too weak to be

detected automatically, but can sometimes be identified by visually inspecting the waveform plots.

In conclusion, the initial results obtained from real time processing of data from NORESS are very encouraging, and have met and in some cases exceeded the expectations. Particularly noteworthy is the excellent P detection in the 2-4 Hz band, which is due to greater than \sqrt{N} noise suppression combined with strong P-wave energy. The automatic detection of secondary phases needs refinement, and in particular the narrow-band filter bank processing should be further investigated.

F. Ringdal

References

- Mykkeltveit, S. and H. Bungum (1984). Processing of regional seismic events using data from small-aperture arrays, Bull. Seis. Soc. Am., 74, 2313-2333.

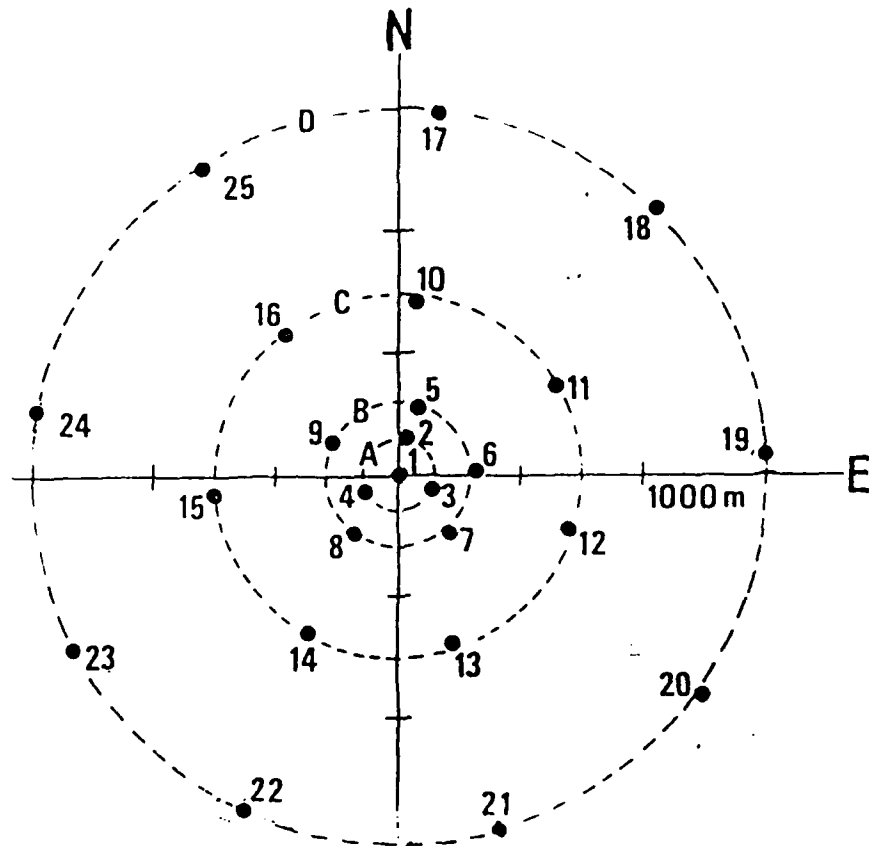


Fig. VII.1.1 Geometry of the NORESS array. The array comprises 25 SPZ seismometers over an area 3 km in diameter. The four rings - A, B, C, D - are marked on the figure.

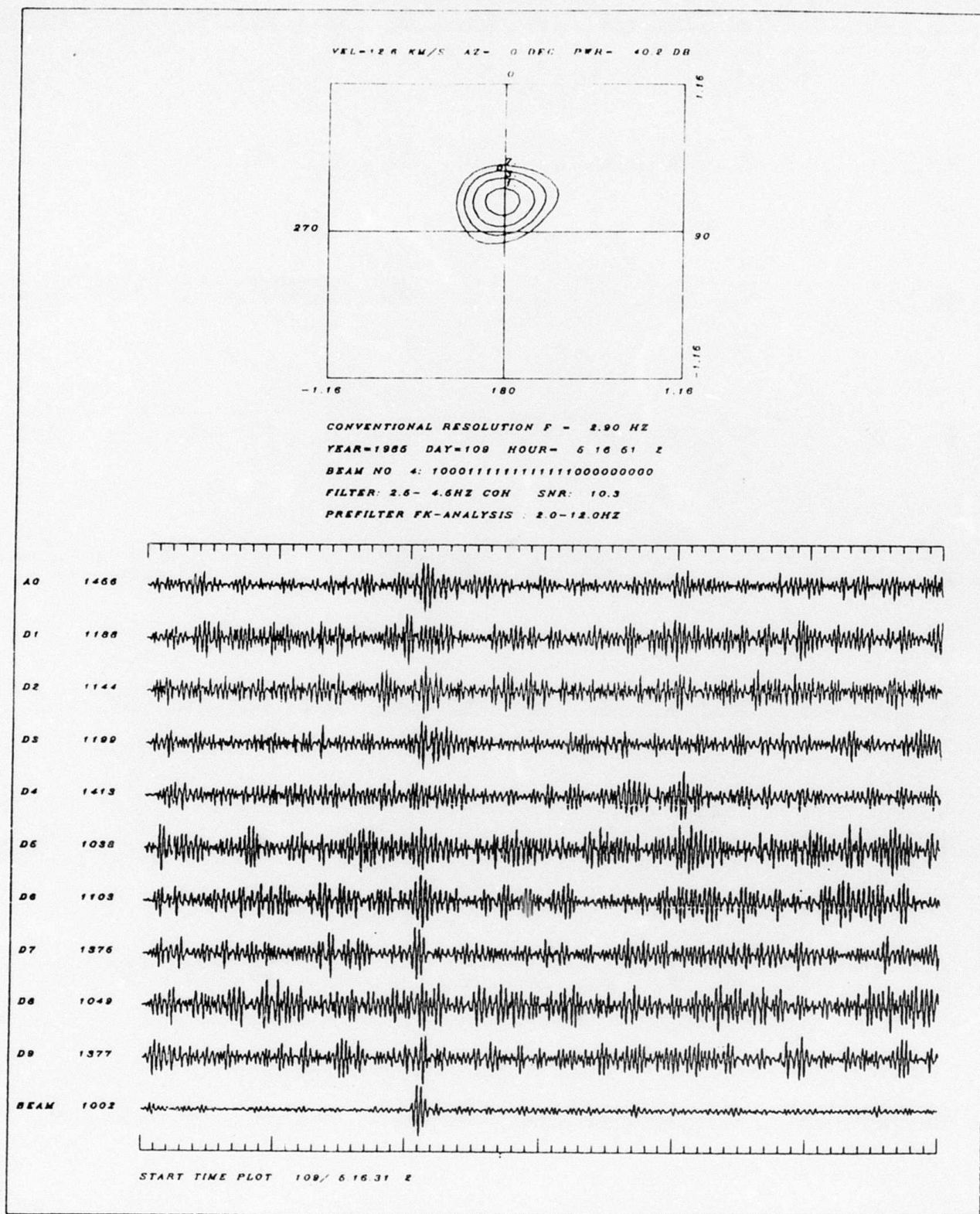


Fig. VII.1.2 Example of automatic processing of a teleseismic event using NORESS. The on-line F-K solution is shown at the top, together with detection parameters. Ten individual sensor traces (filtered 2.5-4.5 Hz) are plotted, together with the array beam (bottom).

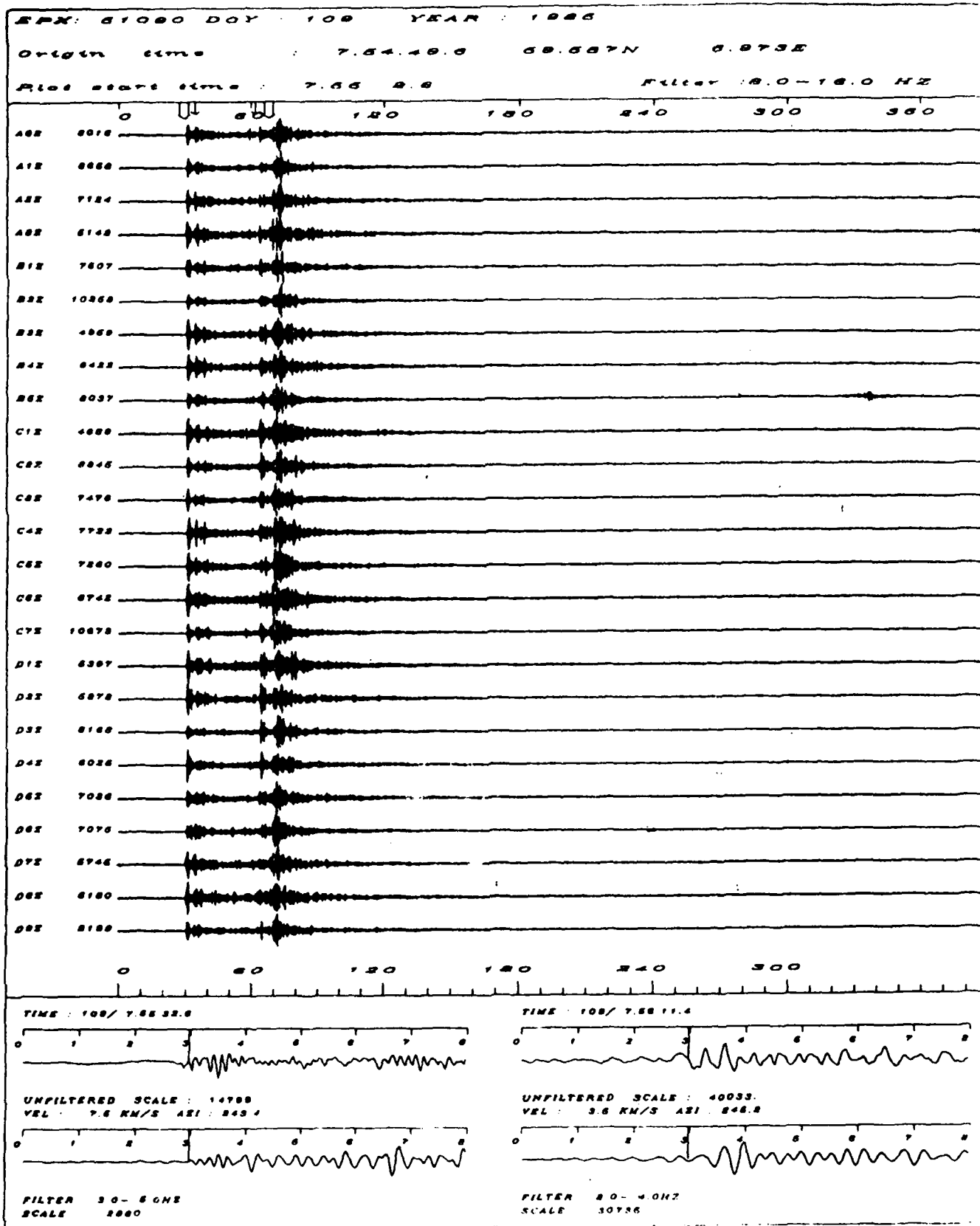


Fig. VII.1.3a Individual NORESS traces for regional event 19 April 1985. The panel covers 6 minutes of bandpass filtered records (8-16 Hz). P and Lg beams are also shown (bottom part).

VII.2 Preliminary evaluation of the event detection and location capability of NORESS

The geometry of NORESS is shown in Fig. VII.2.1. The array has 25 short period vertical seismometers, arranged on concentric rings around the central site. Four of the 25 sites are occupied by three-component seismometers.

A data base of local and regional events has been collected, with the purpose of evaluating the event detection and location capability of the new array. As a first approach, we have concentrated our efforts on the study of a data set of 18 seismic events that occurred in the Baltic and Leningrad regions of the U.S.S.R. during the time period January-March 1985. The events are associated with mining activity and are all reported and located by the Finnish network of seismic stations. An example of one such event is shown in Fig. VII.2.2. Three distinct phases P, Sn and Lg can be seen for all 18 events. Spectra for noise preceding the P onset, the P phase, the Sn phase and the Lg phase are plotted together in Fig. VII.2.3 for one of the events. As can be seen, the P phase is very rich in high frequencies, while Sn and Lg approach the noise level from about 8 Hz. Note also the noise peak at around 6 Hz, which is typical of daytime noise samples.

Now, to assess the detection capability of the array, we have estimated the SNR gain by beamforming for the three phases P, Sn and Lg. This has been done by computing the signal loss and noise suppression and taking the ratio. The signal loss is the spectrum of the beam (with appropriate bearing and velocity depending on the phase type) divided by the average spectrum of all individual channels. Similarly, the noise suppression is the ratio of the spectrum of the noise beam (noise preceding the signal, shifted in the same way as the signal itself for the beamforming) to the average spectrum of all individual channels.

The noise spectra have been estimated using the indirect covariance method. We first estimate the correlation function by splitting a long data record into many windows, calculating a sample correlation function for each window, then averaging the sample correlation functions. Typically, we use 20 windows, each of which is 5 seconds long. Because the earth noise has such a large dynamic range, we prewhiten it prior to estimating the correlation function with a low-order prediction-error filter. The spectrum is then estimated by windowing the correlation function with a 3 second Hamming window, then computing the Fourier Transform. The spectral estimate obtained this way is compensated then for the effects of prewhitening.

The signal spectrum is calculated by windowing the signal with a 10% cosine taper window, 5 seconds long, then calculating the Fourier Transform and finally squaring the transform.

When we do direct comparison of the noise spectrum, which is a power density spectrum, with the signal, which is an energy density spectrum, we divide the signal spectrum by the length of the signal analysis window to convert energy density to power density. The two spectral quantities are then directly comparable. This has been done in Fig. VII.2.3.

The signal loss, noise suppression and SNR gain by beamforming have been computed for four different array configurations:

- All elements included ("ALLV" in the figures)
- All elements minus A-ring ("INTERMEDIATE")
- Center instrument, C-ring and D-ring ("TELEV")
- All elements minus D-ring ("HIFREQ").

In Fig. VII.2.4, noise suppression curves, representing averaging over the 18 events, are shown for all four array geometries. The horizontal lines represent \sqrt{N} suppression of noise, where N is the number of sensors in the geometry under consideration. This is the expected level

for noise that is uncorrelated over the entire array. As can be seen, the "TELEV"-geometry is remarkably good in suppressing the noise in the 1.5-3.5 Hz band, while the other geometries approach the \sqrt{N} level for various frequencies, but do not show better noise suppression than \sqrt{N} . These results partly reflect on the SNR gains shown in Fig.

VII.2.5. the signal losses (not shown) tend to be larger for the larger geometries (including outer rings) because of the decaying signal correlation with increasing station separation. The overall effect is to level the gain curves, and we can see from Fig. VII.2.5 that only at fairly low and fairly high frequencies do the gain curves for the different geometries deviate substantially.

For the Sn and Lg phases, the "noise suppression" estimates reflect suppression by beamforming of the P and Sn coda, respectively, i.e., we address the problem of detecting a secondary phase in the coda of a preceding phase. Results shown in Fig. VII.2.6 are for the Lg phase and correspond to the best SNR result obtained among the four geometries. SNR-gain is now well below \sqrt{N} , essentially because of failure to suppress the Sn coda, which propagates with similar phase velocity and azimuth as the Lg onset. Still, there is a 6 dB gain from beamforming at 1.2 Hz.

Fig. VII.2.7 shows the P onset for a Novaya Zemlja explosion (distance approx. 20°) recorded on NORESS, and the SNR gain by beamforming computed as before for the "TELEV" configuration. In the frequency range 1.0-2.7 Hz the gain is better than \sqrt{N} , because of a very modest signal loss in combination with optimum noise rejection, as for the "TELEV"-configuration in Fig. VII.2.3. The same result is visualized in the time domain in Fig. VII.2.8.

Our approach to the location performance evaluation has been to compute narrow-band FK-spectra for the P, Sn and Lg signals for the events in the data base. FK-spectra have been computed for the array subsets given above and for frequencies corresponding to distinct spectral maxima for each phase. Typical results are given in

Table VII.2.1 for one event. As can be seen, the analysis frequency is the critical parameter, and more so than the array subgeometry used in the evaluation of the FK-spectra. According to these results, then, the arrival azimuth varies fairly strongly with frequency and due care must be taken in selecting the analysis frequency. To gain more insight into these frequency-dependent lateral refraction effects, we have computed the broad-band maximum likelihood FK-spectra for a number of phases. One example is shown in Fig. VII.2.9, where the azimuth's dependency on frequency is given implicitly in the contour plot. The azimuth value of 89.5 serves to illustrate that the broad-band FK tends to give more stable estimates than those derived from narrow-band FK-spectra.

The research effort continues with analysis of events from other regions, in order to obtain the capabilities of the new NORESS array for local and regional events from all source regions of interest. As experience is gained, the results from this study will be utilized directly in the online processing of NORESS data.

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Array	P at 3.40 Hz		P at 6.35 Hz		Sn at 2.20 Hz		Lg at 1.33 Hz		Lg at 1.80 Hz	
	Vel	Az	Vel	Az	Vel	Az	Vel	Az	Vel	Az
HIFREQ	11.71	80.8	9.73	92.3	5.05	86.1	4.55	95.5	4.31	109.0
ALLV	11.58	86.1	10.14	95.8	5.02	84.0	4.29	95.4	4.07	106.9
INTERM	11.52	86.2	10.15	95.9	5.02	84.0	4.29	95.5	4.08	105.7
TELEV	11.51	86.3	10.07	98.1	5.03	84.0	4.28	95.0	4.10	102.3

Table VII.2.1 Narrow-band FK-results for one event in the Baltic-Leningrad region data base.
According to the location reported by the network of Finnish seismic stations, the true azimuth for NORESS is 91.6°.

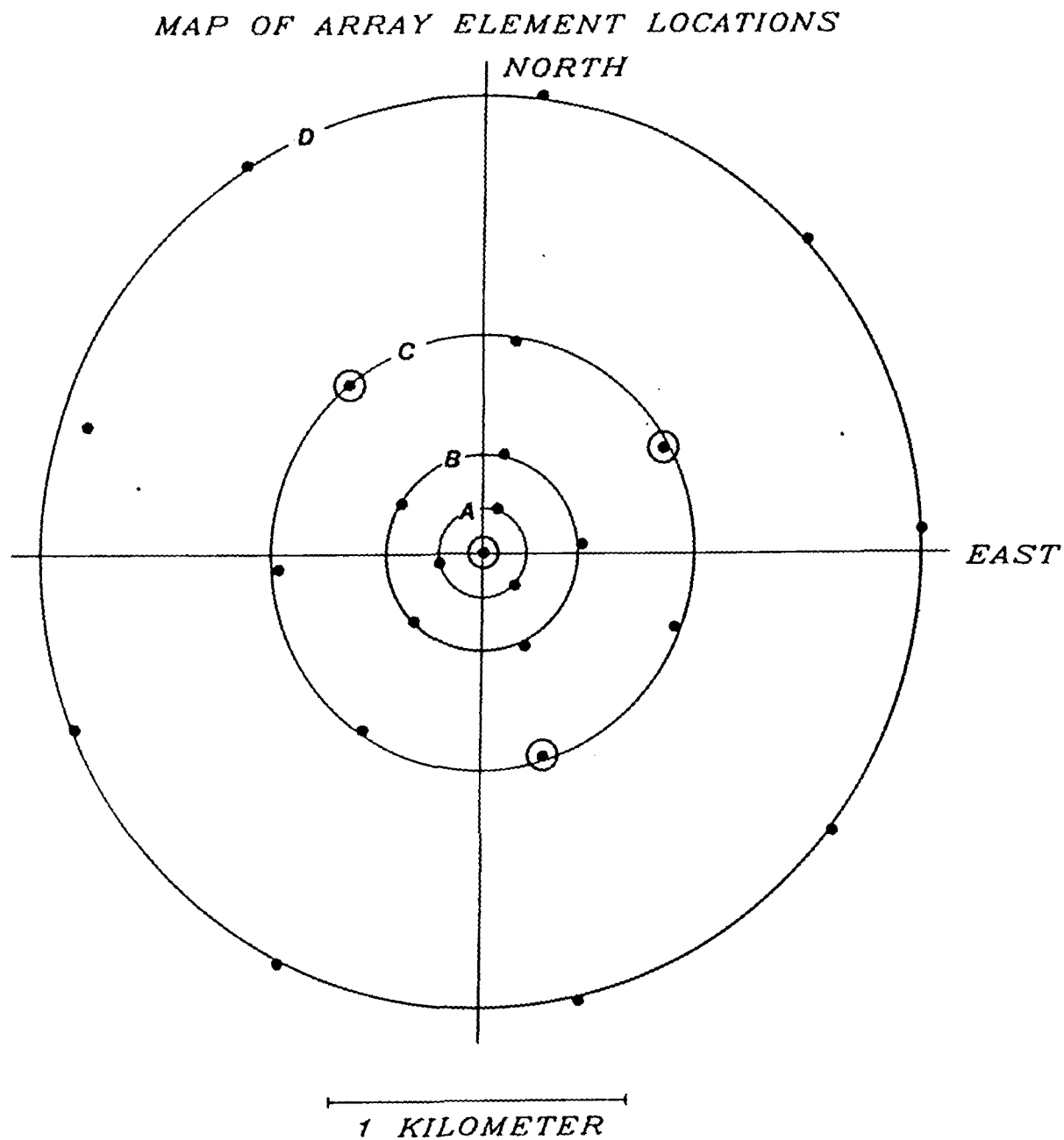


Fig. VII.2.1 Geometry of the new NORESS array. The four three-component stations are marked with special symbols.

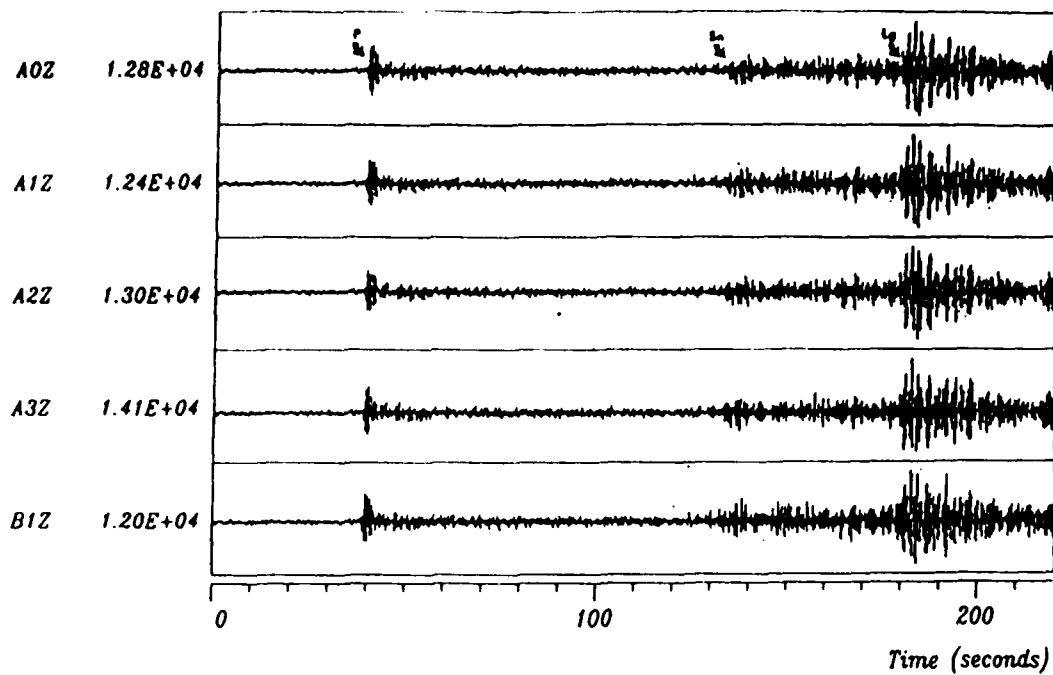


Fig. VII.2.2 Example of event from the Leningrad region, with P, Sn and Lg phases.

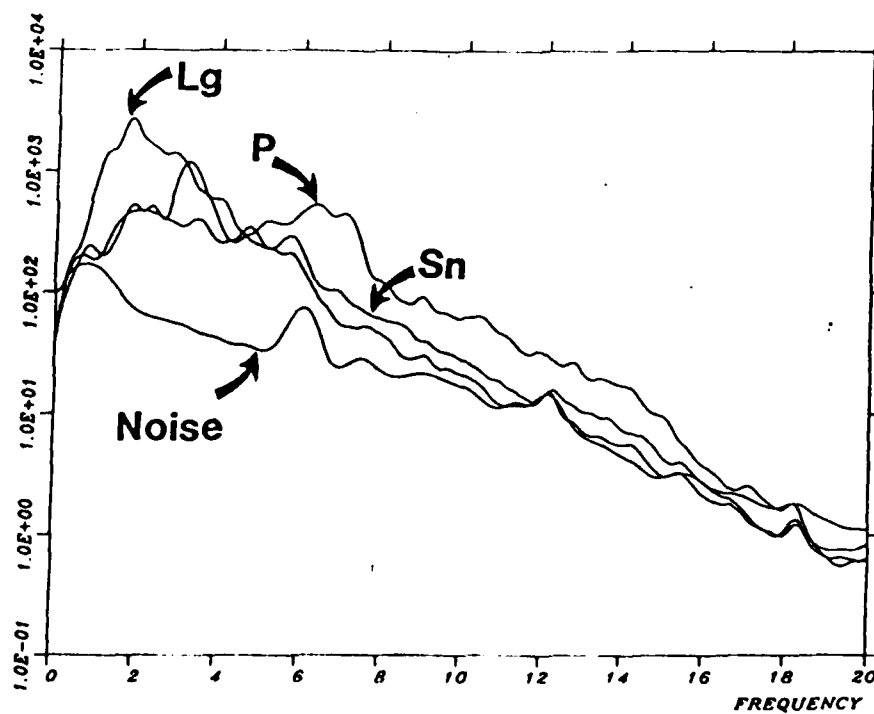


Fig. VII.2.3 Spectra for the P, Sn and Lg in Fig. VII.2.2 and for noise preceding the P arrival.

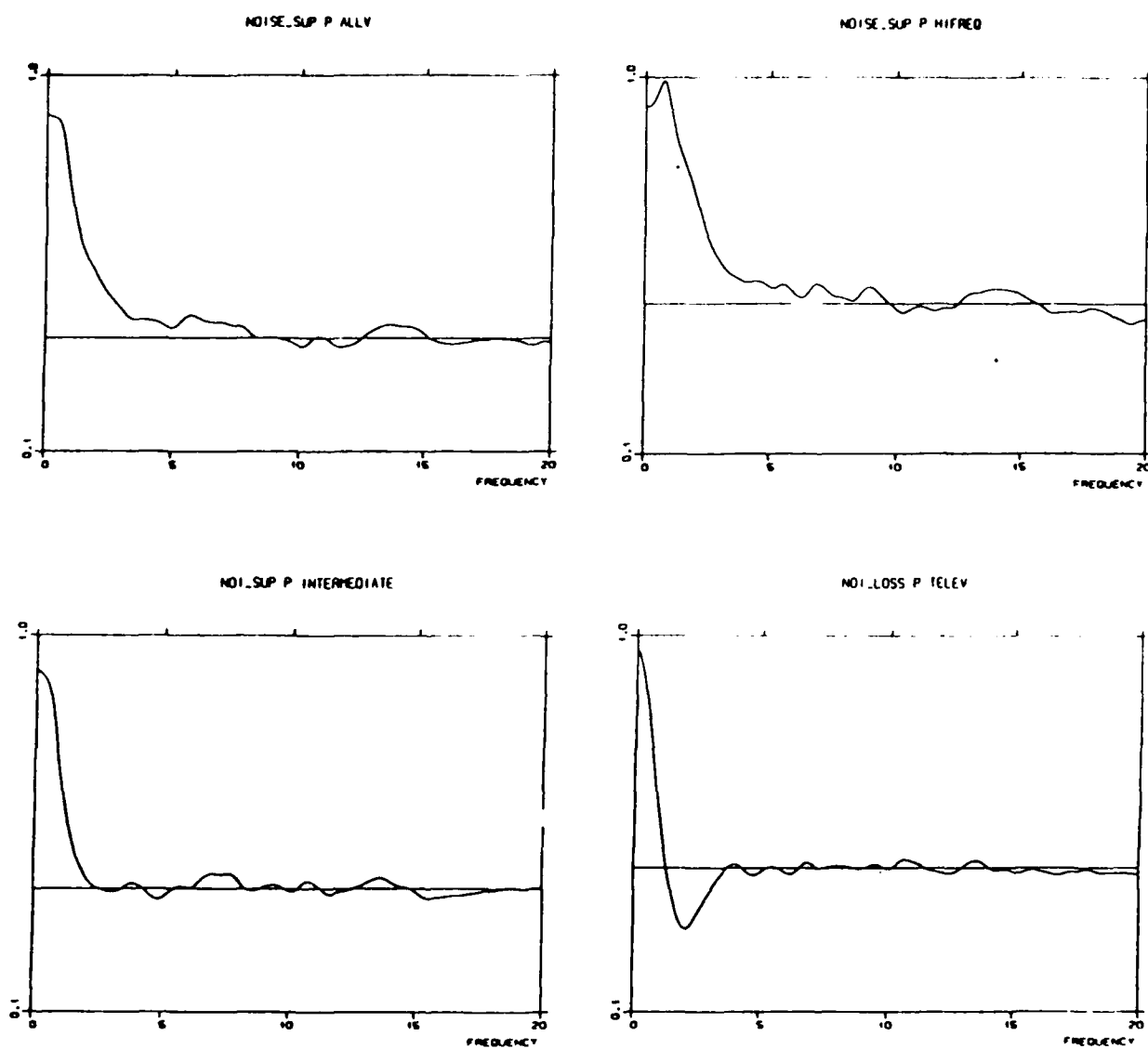


Fig. VII.2.4 Noise suppression for the four array subgeometries. The horizontal line represents $1/N$ noise rejection, where N is the number of sensors in each subgeometry. The vertical scale is logarithmic.

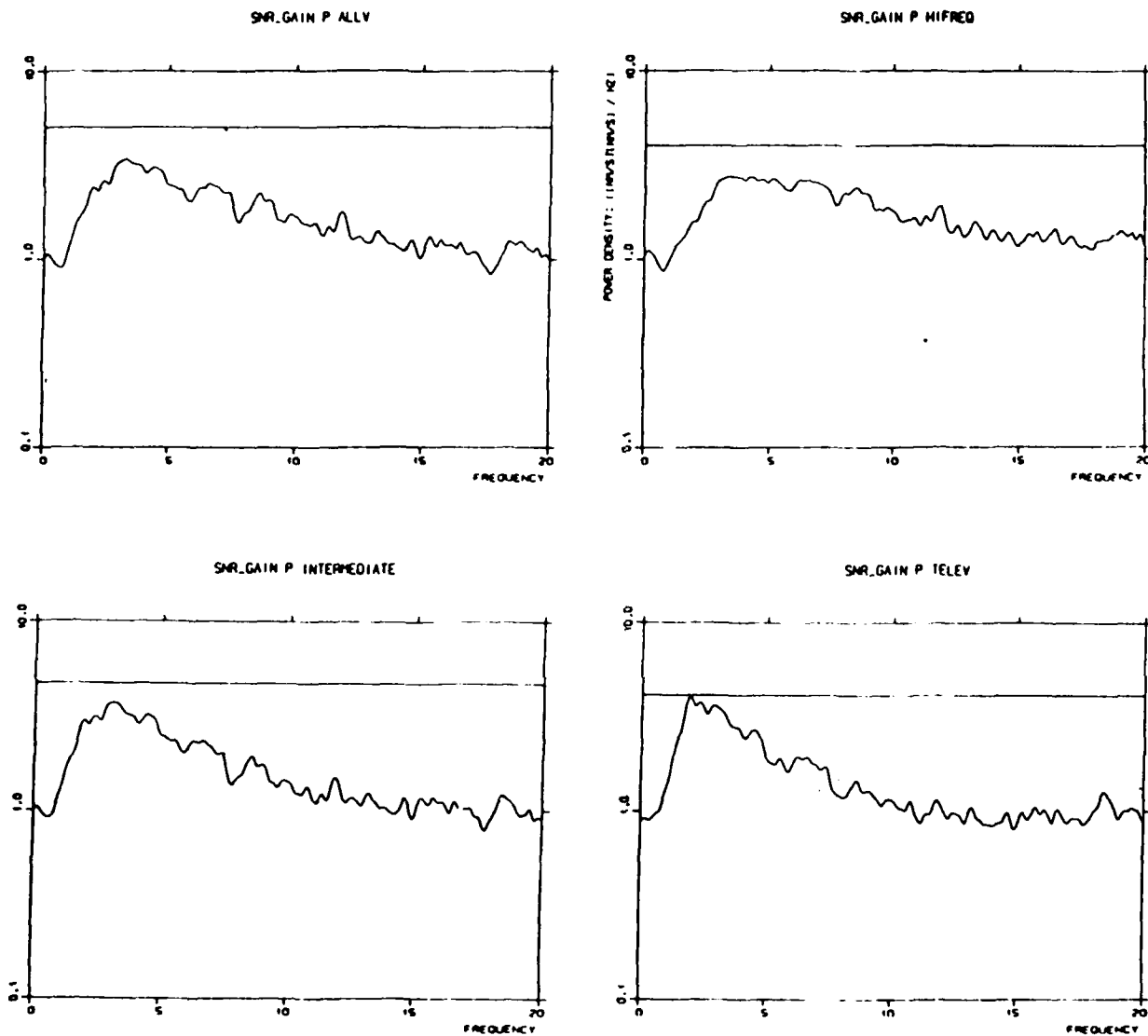
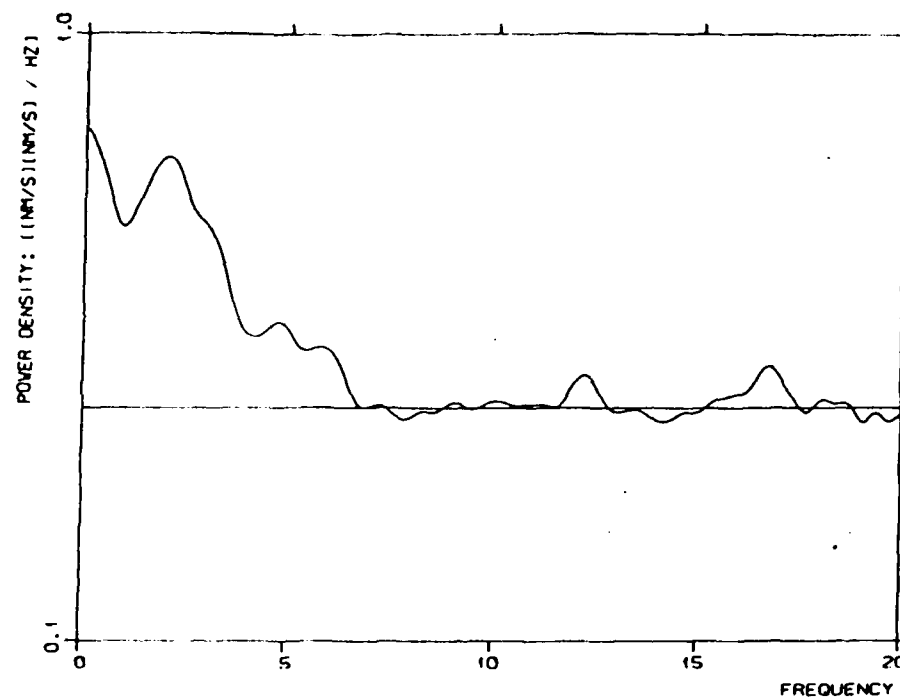


Fig. VII.2.5 SNR gain by beamforming for the four array subgeometries. The horizontal line represents $1/N$ gain, where N is the number of sensors in each subgeometry. The vertical scale is logarithmic.



SNR GAIN TELEV LG-PHASE

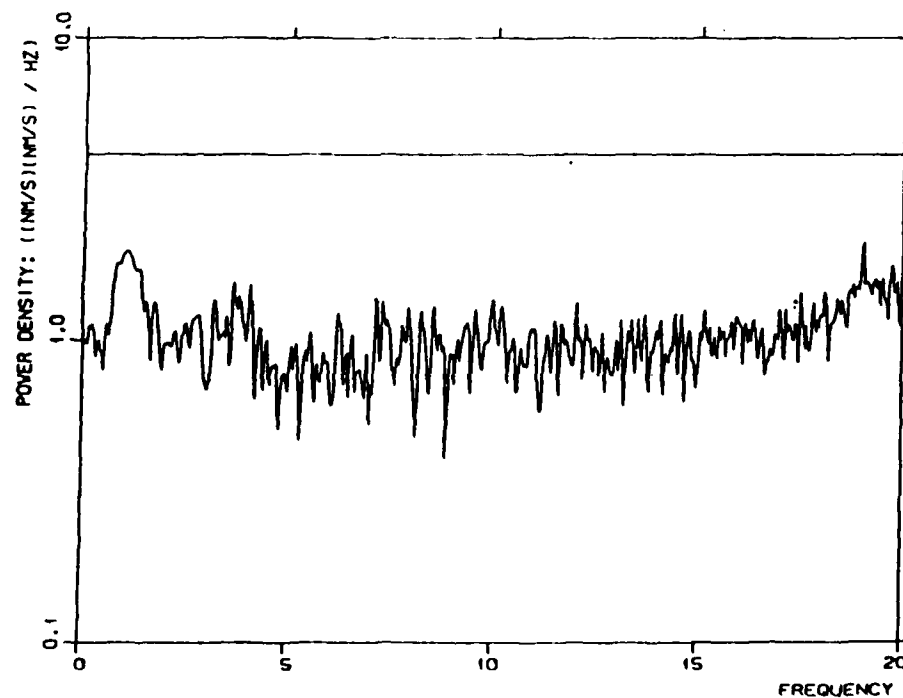


Fig. VII.2.6 Noise suppression and SNR gain for the Lg phase for sub-geometry "TELEV". Horizontal lines represent \sqrt{N} -noise rejection (upper plot) and \sqrt{N} -beamforming gain (lower plot), with $N = 17$ for this subgeometry. Vertical scales are logarithmic.

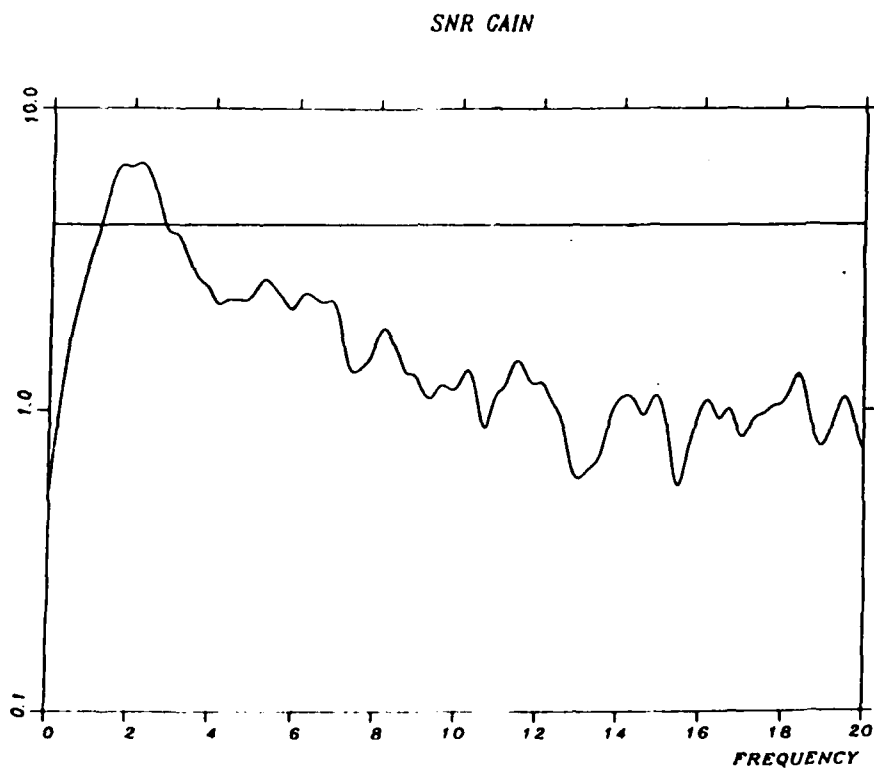
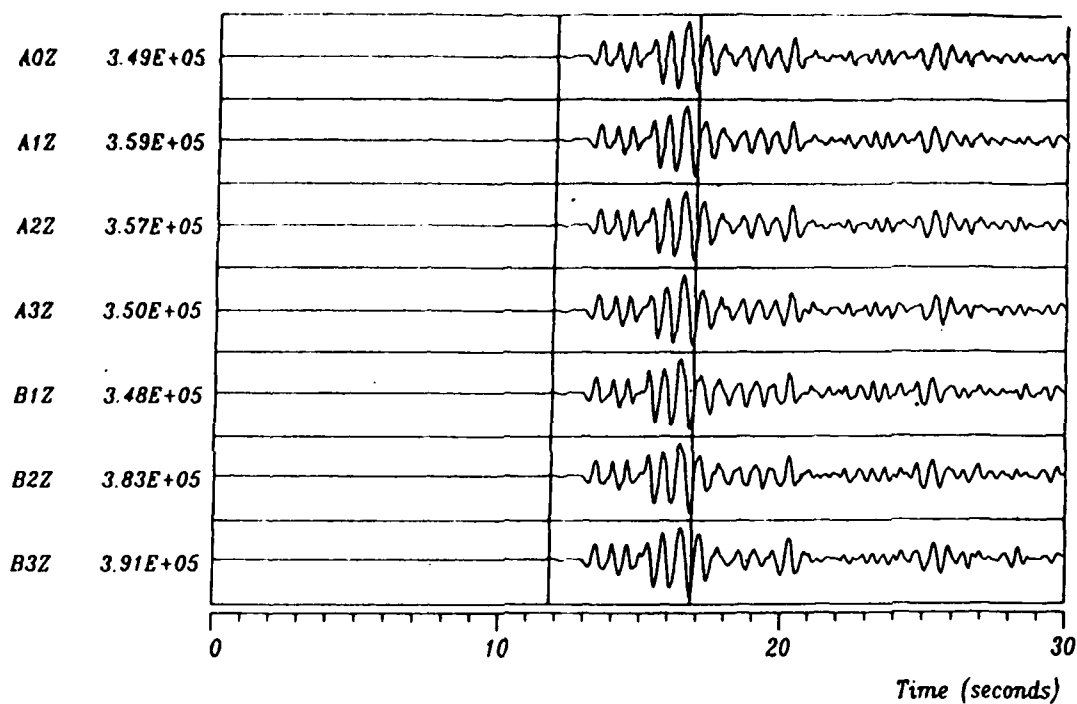


Fig. VII.2.7 Beamforming gain for array "TELEV" for P-arrival from Novaja Zemlja event. P-wave data analysis window on top. The horizontal line in the gain plot indicates $1/N$ gain, with $N = 17$ for this subgeometry.

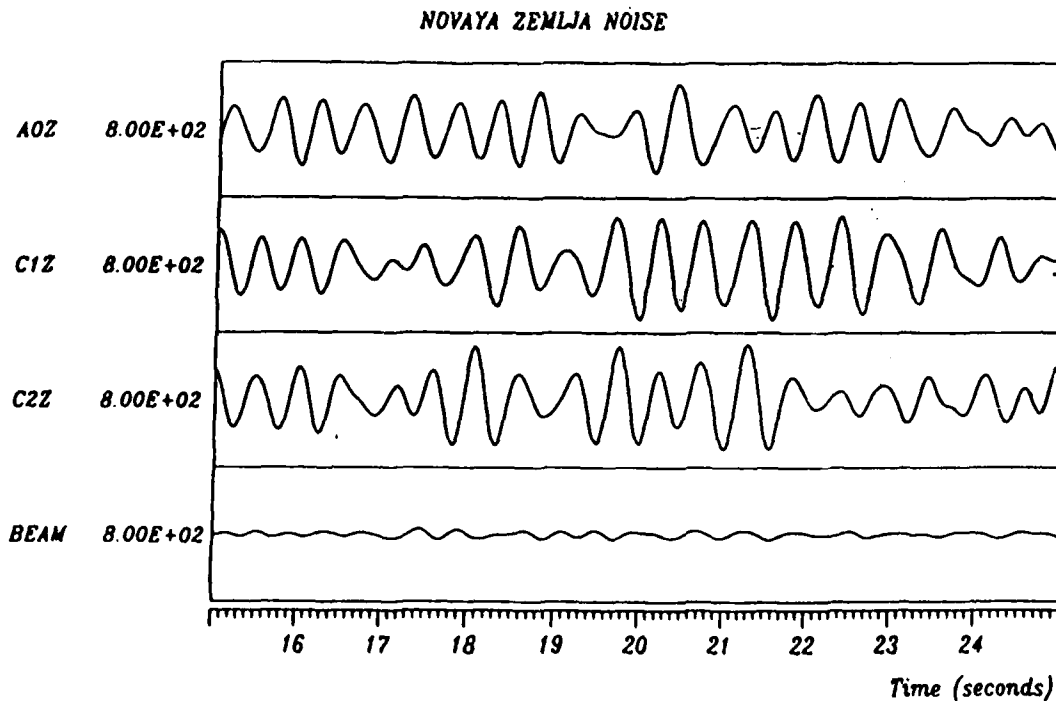
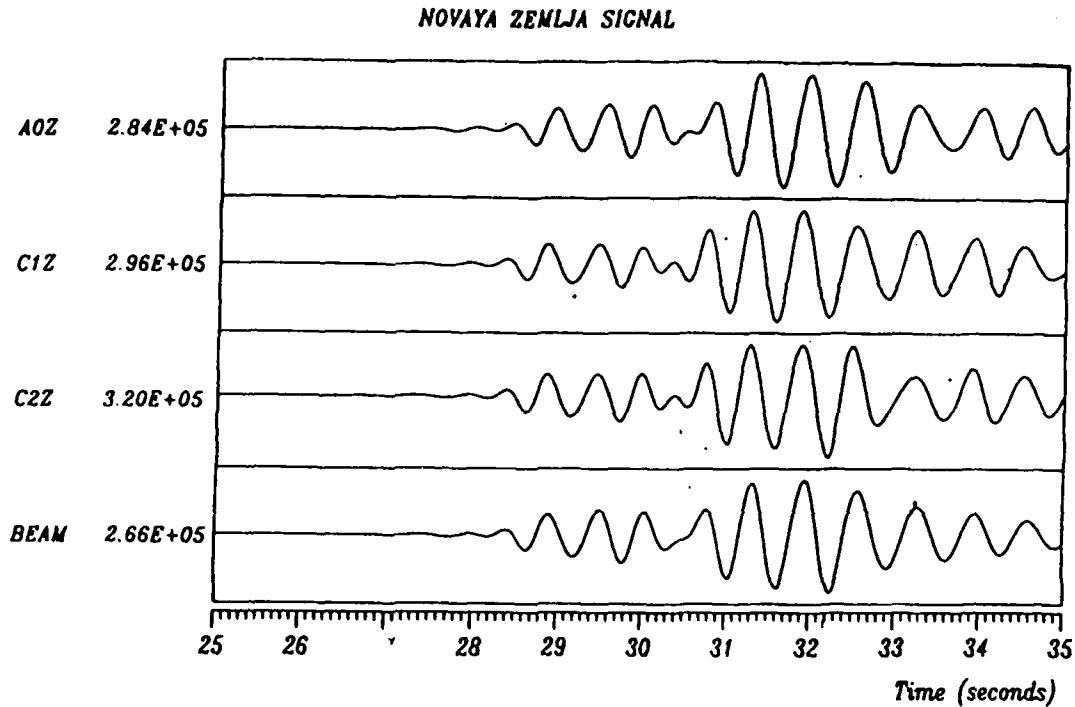


Fig. VII.2.8 Time domain illustration of the SNR-gain results in Fig. VII.2.7. Top: Normalized plot of three single channels (out of the 17 participating in the beam) and the beam, showing a very modest signal loss. Bottom: Noise rejection obtained on preceding noise (true amplitude plot). The filter bandpass is 1.3-2.5 Hz, corresponding to the peak in the gain curve in Fig. VII.2.7.

